E/CONF.39/A/62
3 Oct.1962
ORIGINAL : ENGLISH

UNITED NATIONS CONFERENCE
ON THE APPLICATION OF SCIENCE AND TECHNOLOGY
FOR THE BENEFIT OF THE LESS DEVELOPED AREAS

Agenda Item: A.3.4.3

World Meteorological Organization

ARTIFICIAL INCREASE OF RAINFALL

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ARTIFICIAL INCREASE OF RAINFALL

By

Commission for Aerology Working Group on
Clouds and Hydrometeors

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1. Introduction

(a) The revolutionary prospects of artificial rain-making have attracted the serious attention of all concerned, particularly the atmospheric scientists. The prospects of removing, or at least minimising water deficiency of vast tracts of land surface is so full of promise that numerous attempts have been made in recent years in various countries for producing artificial rain for economic advantages.

(b) The aim of this report is to present a brief objective survey of the present state of knowledge of techniques for attempting to produce artificial increases of precipitation. In 1955, the World Meteorological Organization published Technical Note No.13 giving a detailed discussion of the physics of clouds and summarizing existing knowledge on all aspects of cloud modification. Since the publication of Technical Note No.13, a substantial amount of new information has been accumulated. A large number of cloud seeding projects have been conducted. However, the overall views of this problem as presented in that Technical Note still have general validity.

(c) During the past decade, knowledge of the processes occurring inside clouds has increased significantly as a result of theoretical and experimental investigations. Nevertheless it still is not possible to evaluate quantitatively the processes which lead to the formation of precipitation. Therefore we still lack sufficient information for assessing by means of physical methods (therefore, absolutely objective ones) the effects of seeding on large-scale experiments. For this reason, this report will emphasize the part played by statistical methods for evaluating rain-making experiments.

2. Basic Knowledge

(a) The natural processes which lead to the formation of precipitation inside clouds and which represent the foundations on which techniques of seeding are based, will not be discussed here in any detail. The reader is referred to the appropriate literature on this subject.

(b) Research in cloud physics has demonstrated that there are two processes for the production of precipitation:

(i) When an ice crystal is introduced in a volume of supercooled clouds, it grows at the expense of surrounding droplets. The growth takes place by means of water vapour diffusion followed by the capture of droplets colliding with the falling crystal. The precipitation particles can reach the ground as a snow crystal or a raindrop depending on the value of the temperature in the lower layers of the atmosphere.

(ii) In a volume of cloud a large droplet (30 to 50 microns radius) grows by coalescence with smaller droplets until it becomes a raindrop.

(c) It should be noted that in the evaluation of the efficacy of seeding techniques, the microphysical aspects of the precipitation processes should not be over-emphasized. The spectrum and the concentration of the particles (nuclei droplets and crystals) are not the only parameters to be considered. It is essential to realize that the macrophysical features of the cloud system play an important rôle in the precipitation process. It is clear that the quantity of rain that falls depends on the properties of the atmosphere which governs the growth and maintenance of the clouds.

(i) Various studies have shown that the precipitation efficiency of different raining cloud systems may vary from very low to 100 per cent. When the rate of water vapour deposited on particles in the cloud is equal to the quantity of precipitation falling out of the cloud, there is no storage of water inside the cloud, and the precipitation efficiency may be said to be 100 per cent.

(ii) On the other hand, when the rate of water vapour deposited on the particles is greater than the quantity of precipitation released by the cloud, there is storage of water in the cloud, and the precipitation efficiency is less than 100 per cent. In this circumstance, cloud seeding may augment the natural processes and lead to an increase in rainfall.(1)

(d) It should be recognized, when considering the use of cloud modification techniques, that the physical properties of the clouds should be well known. We know, for example, that there are important differences in the

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(1) It is possible, in the case of 100 per cent efficiency, that the artificial production of ice crystals may lead to a rapid release of the latent heat of fusion of water, causing an increase of the updraft velocity and an increase in precipitation.

cloud and precipitation processes in local convective clouds and widespread cloud systems produced by frontal lifting. It has already been noted that cloud temperatures are important in the precipitation processes. Because of the fact that there are large differences in cloud types and amounts from one region to the next, it is not usually possible to extrapolate the results in one region to another region without first having made fairly extensive series of observations of the clouds. It is strongly urged that provisions be made for collecting appropriate special observations before any cloud seeding is attempted.

3. Seeding Techniques

(a) Seeding substances

(i) Clouds composed of water droplets supercooled to temperatures of -15°C and lower are commonly found in the atmosphere. In order to stimulate precipitation, ice crystals should be produced inside the clouds at lower altitudes than would be the case if the ice crystals develop naturally. The threshold of nucleation can be raised to higher temperatures by means of solid carbon dioxide and finely divided silver-iodide particles. The threshold of the nucleation of CO_2 and AgI are 0°C and -7°C respectively. Other chemical reagents have also been tested as ice-forming nuclei but their thresholds are at temperatures below -7°C.

(ii) For the production of large cloud droplets which can grow efficiently by coalescence, hygroscopic salts and water drops have been dispersed in clouds.

(b) Production of seeding agents

(i) Solid carbon dioxide has been released in clouds in the form of small pellets. The deeper the supercooled parts of the clouds, the larger should be the diameter of the CO_2 pellets released from above. Under the best seeding conditions the rate of production of ice crystals by means of CO_2 has a maximum of the order of 10^{16} crystals per gram.

(ii) Many types of silver-iodide generators have been designed and constructed. It is believed that the largest rate of production of silver-iodide particles, which can be achieved only with great difficulty and highly-refined techniques, is 10^{14} particles per gram of silver-iodide. In general, silver-iodide is vapourised at a high temperature either in a flame or in a hot chamber or as a result of the explosion of substances containing a silver-iodide mixture. The minute particles having diameters ranging from 0.01 to 1 microns are formed by sublimation from the vapour phase. In some experiments, AgI particles are produced as a result of evaporation of droplets of highly valatile liquids containing a colloidal suspension of AgI.

(iii) Hygroscopic particles have been obtained by grinding salt into fine powder or by the spraying of saline solution.

(c) Methods of introducing seeding substances

(i) Dry ice, a relatively inexpensive substance, is usually released from airplanes. New techniques for obtaining particles of CO_2 allow controlled rates of seeding. Although dry ice can be very effective for ice-crystal formation in supercooled clouds, the necessity of using airplanes, at the present time, can limit its application in large-scale experiments.

(ii) Silver-iodide has been released from networks of ground-based generators, from airplanes and rockets. With all types of seeding techniques it is important to consider the transport and diffusion of the silver-iodide particles. In particular, the particles produced at the ground can be transported into clouds only when there is strong convection or a pronounced orographic barrier exists. There is no effective control of the trajectory of the silver-iodide smoke plume when the generators are located on flat terrain. In various experiments, silver-iodide particles have been released from airborne generators on airplanes flying up-wind from the clouds. In this case also, it is essential that the diffusion and transport of the particles by air motions be considered.

a. An important problem encountered when silver iodide particles are released up-wind from the clouds is caused by the decay of the ice-forming properties as a result of exposure to sunlight. The decay rate may be of the order of a factor of 10 per hour.

b. Silver-iodide can be transported directly into the clouds by rockets. An explosive mixture of silver-iodide is placed in the head of the rocket. When the mixture explodes, a high local concentration of silver-iodide particles is produced. The spread of these particles through the cloud is determined by diffusion and turbulent air motions in the cloud.

(iii) Hygroscopic particles have been dispensed from the ground, airplanes and rockets. When the particles are released from the ground a significant fraction of the material is lost. The very large particles fall to the ground in the vicinity of the generator. The uncertainties connected with the trajectories of salt are even more serious than is the case for silver-iodide because the salt particle diameters are much greater than those of the silver-iodide.

4. Statistical evaluation procedures

(a) Since the late 1940's a variety of statistical techniques has been tried. Some of them have since been shown to be insensitive and have been discarded; others are still in use. In general, the schemes that have been employed can be divided into two categories: 1) those which involve only a single area over which more precipitation is wanted and which is often called the "target area"; 2) those which involve two regions, the target area and another nearby region, known as the "control area", whose precipitation is used to estimate the natural precipitation which would have fallen over the target area had there been no seeding. In the following paragraphs the prominent features of these two categories of statistical designs will be discussed briefly.

(b) Some of the early cloud-seeding tests were made by seeding over a particular area and comparing the precipitation with that which fell in the past over the same area. It has been reported by H.C.S. Thom[2] that because of the high variability usually encountered, it would be necessary for cloud seeding to increase precipitation to about three times its medium value in order to be able to demonstrate at a convincing level of statistical significance (the 0.05 significance level) that there was an increase of precipitation. In view of the fact that, at the present time, cloud physicists believe about a 20 per cent increase is a reasonable upper limit to a possible increase, the use of a single area and a comparison of seeded rainfall with historical records, seems unlikely to demonstrate the occurrence of reasonable rainfall increases even if they actually occur.

(c) A second cloud-seeding evaluation procedure by which only one area is used, involves the seeding of approximately half the suitable cloudy periods and then comparing the precipitation on the seeded and not-seeded periods. For example, if there is a distinct diurnal maximum of rainfall, a day can be selected as the experimental unit. When suitable cloud conditions are expected, each day is either seeded or not, according to a suitable randomization scheme. By employing an objective technique for deciding when days are suitable, it is possible to design an experiment whereby one of two successive days is seeded on a random basis. The evaluation involves the study of pairs of days. The sensitivity of this type of approach depends, to an important extent, on the correlation between rainfall on the two successive days which constitute the pairs. The higher the correlation between rainfall on two successive days, the more sensitive the tests.

(d) A commonly used cloud-seeding evaluation procedure involves two nearby areas only one of which is seeded. If the precipitation quantities on the two areas are highly correlated, the precipitation on the unseeded (control) area can be used to estimate the quantity of precipitation which would have fallen on the seeded (target) area had it not been seeded. This so-called "regression-analysis technique" of predicting target rainfall has some weaknesses. First of all, it requires extensive periods of rainfall records and therefore can be applied in only a limited number of places. It is based on a mathematical model which assumes that the rainfall quantities on the two areas are drawn from a stationary and normally distributed time series. Neither of these assumptions is entirely justified. Departures of precipitation amounts from normality can be corrected in part by transforming the measured rainfall to a variable which is close to normality. This has been done by using the logarithm or the square root of the precipitation. The measured precipitation values can also be transformed to approximately normally distributed functions by making use of the finding that precipitation data is closely fitted by the incomplete gamma distribution. It is not clear, however, that this more complicated transformation is any better than the simpler ones. It has been found that when the transformed target precipitation is plotted against the transformed control precipitation, the variability of the former remains essentially constant for all values of the control

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(2) Final Report of the Advisory Committee on Weather Control, Vol.II, U.S. Government Printing Office, 8 (1957).

precipitation. Once this has been accomplished, it is possible by means of standard statistical techniques to calculate the probability that the results during seeded periods could have resulted by chance.

(e) A serious difficulty in using regression methods is introduced by time variations in the relationship between the rainfall on target and control areas. It is well-known that precipitation undergoes cycles of varying wavelengths and durations. Over a period of several years area A may have more precipitation than area B, possibly because of a prevailing wind pattern favouring deep-cloud formations over A; during the next several years the prevailing pattern may shift so as to give more rainfall over area B. In order to take such temporal variations into account, long periods of records are needed. Unless they exist, the seeding evaluation scheme is subject to some question. In some cases it may be possible to reduce the effects of weather cycles by stratifying the data according to a system of storm types and developing a regression line of target versus control transformed precipitation for each storm type. Unfortunately, in most regions the quantity of historical data is not sufficient to allow for much stratification.

(f) In the preceding two sections the evaluation involved the comparison of rainfall over two fixed areas. In some programmes, the location of the target and control areas are shifted according to the wind pattern and other meteorological factors. In these tests the areas are delineated at the start of the seeding period and then one or the other, or neither of them, is seeded according to a suitable randomization scheme. The average precipitation over the seeded and not-seeded areas can then be compared. Clearly, a large number of raingauges is needed if the tests are concerned directly with the effects of seeding on precipitation reaching the ground.

(g) A randomized seeding programme is one in which the test occasions are divided into two groups, one of which receives the seeding treatment and the other of which does not, the selection of cases for the two groups depending solely upon random events. The evaluation of the effect of the treatment is then obtained from the difference in precipitation in the two sets of data.

(i) The effect of randomization is to provide a simple and complete guarantee of a valid interpretation of the results of a test, regardless of disturbances and uncertainties arising from incomplete control over the conditions of the test[3]. In previous sections it was noted that errors may result from bias in the mode of operation or method of evaluation, and may also arise from the effects of selection of covariates, and from the general failure of weather sequences to behave as stationary time series. Methods of minimizing such errors have been discussed, but it has also been pointed out that at present there is no way of eliminating them entirely, and no reliable way of determining their magnitude. Randomization is an effective way of placing the experimentation on a meaningful basis.

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(3) Fisher, R.A.: The Design of Experiments, 2nd ed. Oliver and Boyd, Edinburgh, 22 (1937).

(h) Statistical tests

(i) As noted in paragraph 4(d), when employing regression methods of comparing target and control precipitation, it is necessary to transform the precipitation values so that the variability of target precipitation remains constant for all values of the control precipitation. This step is necessary because regression theory is valid only for normally distributed variables.

(ii) The difficulty of non-normally distributed variables can be overcome by employing non-parametric tests which, by definition, do not require a knowledge of the distribution of the test variables.

(iii) It is essential to recognize that in order for any cloud-seeding experiment to yield convincing statistical results, it is necessary that the technique of data collection be compatible with the technique of data analysis. For example, if it is decided to use a randomization scheme whereby one of two suitable pairs of days is seeded randomly, the tests of significance should be made by means of a procedure which examines the difference between the rainfall on the pairs of days.

(iv) Statistical techniques of evaluation are essential because of our poor understanding of natural precipitation processes and our inability to accurately predict the quantity of rainfall to be expected from any cloud or cloud system. Unfortunately, statistical evaluation techniques are usually insensitive and require large quantities of data before valid inference can be drawn. This fact has made it difficult to resolve the questions about the effects of cloud seeding on precipitation.

(v) Clearly, it is imperative that increasing attention be devoted to studies of natural cloud and precipitation processes so that evaluation of various cloud-modification techniques can be made by physical, as well as by purely statistical methods.

5. Conclusions

(a) The small scale experiments have clearly demonstrated that seeded clouds are significantly modified physically but for evaluation of the increase in precipitation to the ground resulting from the cloud modification, more severe statistical tests have to be applied.

(b) A detailed survey of cloud-seeding experiments performed by means of ground-based AgI generators mostly in the United States was published in 1957 by a government committee of the United States(4). The chief conclusions were the following:

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(4) Final Report of the Advisory Committee on Weather Control, Vols.I and II. U.S. Government Printing Office, (1957).

"(1) The statistical procedures employed indicated that the seeding of winter-type storm clouds in mountainous areas in western United States produced an average increase in precipitation of 10 to 15 per cent from seeded storms with heavy odds that this increase was not the result of natural variations in the amount of rainfall.

(2) In non-mountainous areas, the same statistical procedures did not detect any increase in precipitation that could be attributed to cloud seeding. This does not mean that effects may not have been produced. The greater variability of rainfall patterns in non-mountainous areas made the techniques less sensitive for picking up small changes which might have occurred there than when applied to the mountainous regions.

(3) No evidence was found in the evaluation of any project which was intended to increase precipitation that cloud seeding had produced a detectable negative effect on precipitation."

(c) Conclusion (1) which has been the basis for optimism has been criticised by various statisticians on the grounds that the data employed in the evaluations were not collected by means of a randomized programme (5).

(d) Since 1957 randomized cloud-seeding programmes have been conducted in various countries: notably Australia, France, India, Israel, Italy, Japan, Mexico, Pakistan, Soviet Union, Switzerland and the United States. These tests have thus far not succeeded in demonstrating conclusively that seeding can increase precipitation by a significant amount.

(e) Reports from Australia, where randomized cloud-seeding programmes have been in progress since about 1957, have been mixed. Success has been reported in one project, and possibly a second one as well, while in the other tests the results have either been inconclusive or have shown negative results. Progress reports from several other countries have indicated increases of precipitation, but the data have not yet been published and subjected to the careful scrutiny of the scientific community.

(f) Although there is some evidence that in certain special situations it may be possible to increase precipitation, a net increase of precipitation has not been demonstrated beyond reasonable doubt. Before it can be said that the doubt has been removed, those experiments now in progress which have shown positive results, will have to be taken to their conclusions and the results subjected to the evaluation by stratisticians and atmospheric scientists.

(g) It is the considered opinion of the authors of this report that increasing the knowledge of the natural processes in the clouds and the improvement of the techniques of seeding should lead to the development of effective means for increasing precipitation at the ground.

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(5) Brownlee, K.A., Statistical evaluation of cloud seeding operations. Journal American Statistical Association, 55, 446-453 (1960).

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